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Resonances interference effects on $^{233, 235}U$ nuclei

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Abstract

The asymmetry effects (as forward – backward (FB), left – right (LR) and parity non conservation (PNC)) observed in the fission induced by thermal and resonant neutrons on $^{233, 235}U$ nuclei in the frame of the formalism of mixing states of compound nucleus with the same spin and opposite parities were explained. In this work new P resonance parameters from FB and LR effects in order to explain the observed asymmetries and PNC effect have been derived.
The present study demonstrates by using the multilevel Breit – Wigner formalism that the resonance states observed in FB and LR measurements are just a result of multilevel interference between S resonances. Only new P resonances, not indicated in nuclear data atlases for neutron resonance parameters, are enough to describe the asymmetry effects.

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Keywords: ^{233}U ; ^{235}U ; neutron fission ; resonance interference ; assymetry effects ; parity non conservation

1. Introduction

More than 70 years ago the asymmetry effects in the first experiments on fission process induced by slow neutrons were observed. These effects were explained by (Bohr, 1955; Bohr and Mottelson, 1971), supposing the existence of some P-resonances and by introducing the fission channels of cold fission stage.

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Nomenclature	
S	S resonance
P	P resonance
$W(\Omega)$	angular correlation
PC	parity conservation
α_{FB}	forward – backward coefficient (FB)
α_{LR}	left – right coefficient (LR)
α_{PNC}	parity non – conservation coefficient (PNC)
W_{SP}	weak matrix element, eV

In 1964 the parity non – conservation effects in the capture of polarized slow neutrons by ^{113}Cd nucleus were observed by (Abov et al., 1964), followed by later results on parity violation effects on other reactions and nuclei. This new phenomena in nuclear reaction by the formalisms proposed by (Flambaum and Sushkov, 1984; Flambaum and Gribakin, 1995; Bunakov and Gudkov, 1981), were described. In the frame of these formalisms the asymmetry effects result from the interference between resonances with the same spin and opposite parities. In many analyzed cases involving incident slow neutrons the Flambaum – Sushkov formalism of the two levels approximation was used by (Sushkov and Flambaum, 1982).

In 1976 parity non conservation effects in fission process induced by slow neutrons on ^{233}U, ^{235}U, ^{239}Pu (Danilyan, 1980) were evidenced. In references (Alfimenkov et al., 1999; Alfimenkov et al., 2000), the authors analyzed the asymmetry effects on $^{233,\,235}$U nuclei in the frame of approach of (Flambaum and Gribakin, 1995), proposing for this about 20 new *P* resonances.

In the present work the authors evaluated the asymmetry effects of fission process induced by slow neutrons on $^{233,\,235}$U nuclei using the Flambaum – Sushkov approach showing that such large number of P resonances is not necessary.

2. Theory

In the papers of (Alfimenkov et al., 1999; Alfimenkov et al., 2000), the experimental data of asymmetry effects in the neutron fission of $^{233,\,235}$U in a large energy interval up to about 100 eV were analyzed. The asymmetry effects investigated were the forward – backward (FB), left – right (LR) and parity non conservation (PNC). Theoretical evaluation using the formalism of the mixing states of the compound nucleus with the same spin and opposite parities was done by (Flambaum and Gribakin, 1995; Bunakov and Gudkov, 1981). This approach supposes that by interaction of neutrons with target a compound nucleus is formed which is described by resonant states with fixed quantum numbers. If two resonances have the same spin and opposite parities, then it's possible to observe experimentally the asymmetry effects. For each effect an asymmetry coefficient included in the general expression of angular correlation corresponds:

$$W(\Omega)=1+\alpha_{FB}\left(\vec{n}_n\cdot\vec{n}_f\right)+\alpha_{LR}\,\vec{\sigma}\cdot\left(\vec{n}_n\times\vec{n}_f\right)+\alpha_{PNC}\left(\vec{\sigma}_n\cdot\vec{n}_f\right)=1+\alpha_{FB}\cos(\theta)+\alpha_{LR}\sin(\theta)\cos(\varphi)+\alpha_{PNC}\sin(\theta)\cos(\varphi) \quad (1)$$

where $\vec{n}_n, \vec{n}_f$ = directions of the incident neutrons and of the fission fragment, respectively; $\vec{\sigma}_m$ = neutron spin; α_{FB}, α_{LR}, α_{PNC} = FB, LR, PNC coefficients; θ, ϕ = polar and azimuth angle.

From relation (1) it is easy to interpret that the FB, LR and PNC effects represent correlation between vectors of incident and exit channels through some vector operations like scalar (·) and vector product (×). Also, relation (1) suggests the relations of definition for asymmetry coefficients as:

$$\alpha_{FB} = \frac{W(0) - W(\pi)}{W(0) + W(\pi)}, \quad \alpha_{LR} = \frac{W(0.5\pi, 1.5\pi) - W(0.5\pi, 0.5\pi)}{W(0.5\pi, 1.5\pi) + W(0.5\pi, 0.5\pi)}, \quad \alpha_{PNC} = \frac{W(0.5\pi, 0) - W(0.5\pi, \pi)}{W(0.5\pi, 0) + W(0.5\pi, \pi)} \tag{2}$$

According to this formalism the asymmetry effects result in the interference between the fission reaction amplitudes. There are two types of amplitudes. The first type describes the strong nuclear interaction (where the spatial parity is conserved) and due to the amplitude interference yields the FB effect and, in the case of transversal polarized incident neutrons, the LR effect. The second type of amplitudes describes the non leptonic weak interaction (violating the spatial parity) and in the case of polarized neutrons it is possible to observe PNC effect as well as other more complicated space and time parity non conserving effects described in papers of (Flambaum and Gribakin, 1995; Bunakov and Gudkov, 1981).

The fission case is theoretically detailed treated in (Sushkov and Flambaum, 1982). Using the expression of angular correlation and the relations of definition for asymmetry effects (2) and taking into account only S and P resonances the following expressions for the angular correlations are (3) (PC case) and (4) (PNC case):

$$W_{PC}\left(\vec{n}_f\right) \sim \sum_{S,S'} (2J_S + 1) U_S U_{S'}^* + \sum_{SPj} Q(J_S J_P KI) \mathrm{Re}\left\{ U_S U_{Pj}^* \left(\left(\vec{n}_n \cdot \vec{n}_f \right) - i\beta_j \left(\vec{\sigma}_n \cdot \left[\vec{n}_n \times \vec{n}_f \right] \right) \right) \right\} \tag{3}$$

$$W_{PNC}\left(\vec{n}_f\right) \sim \sum_{S,S''} (2J_S + 1) U_S U_{S'}^* + \sum_{SPj} Q(J_S J_P KI) \mathrm{Re}\left\{ U_{SP} U_{S'}^* \left(\vec{\sigma}_n \cdot \vec{n}_f \right) \right\} \tag{4}$$

The terms in the (3) and (4) relations are the following:

$$U_S = \pm \frac{\sqrt{\Gamma_S^n (J_S) \Gamma_S^f} \exp\left(i\phi_S^f\right)}{E - E_S + i\dfrac{\Gamma_S}{2}}, \quad U_{Pj} = \pm i \frac{\sqrt{\Gamma_P^n (J_P, j) \Gamma_P^f} \exp\left(i\phi_P^f\right)}{E - E_P + i\dfrac{\Gamma_S}{2}}, \quad U_{SP} = \pm \frac{\sqrt{\Gamma_S^n (J_S) \Gamma_P^f} \exp\left(i\phi_P^f\right)}{\left(E - E_S + i\dfrac{\Gamma_S}{2}\right)\left(E - E_P + i\dfrac{\Gamma_P}{2}\right)} W_{SP}$$

where W_{SP} = weak matrix element; ϕ_S^f, ϕ_P^f = phases of the emitted fission fragments; β_j, $Q(J_S J_P KI)$ = parameters depending on the compound nucleus spins J_S, J_P, on the projection of the compound nucleus spin on the fission axis (K) and of the total momentum of neutron target spin (I) (Sushkov and Flambaum, 1982).

(Alfimenkov et al., 1999; Alfimenkov et al., 2000), extracted from FB and LR effects new data on P resonances not indicated in the Atlas of (Mughabghab, 1984), but they have neglected resonance interference in the cross section. It is supposed that these new P resonances can't be observed experimentally because they are very thin in comparison with the S ones. In the present work the interference of every pairs with the same spin and parity of the S and P resonances in the cross section were analyzed because these interferences can influence the shape and magnitude of the effects. In this paper about 20 S and P-resonances were considered. According to (Wigner, 1946), two resonances with the same spin and parity can give non zero contribution in the cross section. Therefore in the expressions (3) and (4) the term indicating the interference between P-resonances will be added. So, expressions (3) and (4) become:

$$W_{PC}\left(\vec{n}_f\right) \sim \sum_{S,S'} (2J_S + 1) U_S U_{S'}^* + \sum_{P,P'} (2J_P + 1) U_P U_{P''}^* + \sum_{SPj} Q(J_S J_P KI) \mathrm{Re}\left\{ U_S U_{Pj}^* \left(\left(\vec{n}_n \cdot \vec{n}_f \right) - i\beta_j \left(\vec{\sigma}_n \cdot \left[\vec{n}_n \times \vec{n}_f \right] \right) \right) \right\} \tag{5}$$

$$W_{PNC}\left(\vec{n}_f\right) \sim \sum_{S,S'} (2J_S + 1) U_S U_{S'}^* \sum_{P,P'} (2J_P + 1) U_P U_{P'}^* + \sum_{SPj} Q(J_S J_P KI) \mathrm{Re}\left\{ U_{SP} U_{S'}^* \left(\vec{\sigma}_n \cdot \vec{n}_f \right) \right\} \tag{6}$$

The interferences in the cross section of pairs (i,j) of S and P resonances have the form by (Oprea, 2010):

$$\sigma_{SiSj} = \pm\eta_{SiSj} 2g_{SiSj}\pi\lambda^2\left[(E-E_{Si})(E-E_{Sj})+\frac{\Gamma_{Si}\Gamma_{Sj}}{4}\right]\left\{\left[(E-E_{Si})^2+\frac{\Gamma_{Si}^2}{4}\right]\left[(E-E_{Sj})^2+\frac{\Gamma_{Sj}^2}{4}\right]\right\}^{-1}\sqrt{\Gamma_{Si}^n\Gamma_{Sj}^n\Gamma_{Si}^f\Gamma_{Sj}^f} \quad (7)$$

$$\sigma_{PiPj} = \pm\eta_{PiPjj} 2g_{PiPj}\pi\lambda^2\left[(E-E_{Si})(E-E_{Sj})+\frac{\Gamma_{Si}\Gamma_{Sj}}{4}\right]\left\{\left[(E-E_{Si})^2+\frac{\Gamma_{Si}^2}{4}\right]\left[(E-E_{Sj})^2+\frac{\Gamma_{Sj}^2}{4}\right]\right\}^{-1}\sqrt{\Gamma_{Pi}^n\Gamma_{Pj}^n\Gamma_{Pi}^f\Gamma_{Pj}^f}\,h_{PiPj}(X,Y) \quad (8)$$

Further we did not use the fitted values for phases in the asymmetry effects calculation. Instead we followed the standard way as in (Bunakov and Gudkov, 1981) or (Oprea, 2010), with phases given by:

$$\Delta\phi_{total} = \Delta\phi_{neutron} + \Delta\phi_{Coul} = kR + e^2 Z' Z \cdot (\hbar v_{rel})^{-1} \quad (9)$$

where k = reduced wave number, R = radius of nucleus, e = elementary electric charge, $\hbar$ = reduced Planck constant, Z, Z′ = charges of the fragments.

3. Results and discussion

The asymmetry effects in ^{233}U and ^{235}U fission induced by resonance neutrons by the above formalism (relations (1)-(9)) were calculated (Figs 1-3). The experimental data without any fit procedures have been qualitatively described. In both papers (Alfimenkov et al., 1999; Alfimenkov et al., 2000), dedicated to the neutron fission of ^{235}U and ^{233}U, respectively, the interference between P resonances were neglected; phases, energies of P resonances, neutron and fission widths were considered as fit parameters (more than 60).

We have considered, with phases defined by relation (9), in one case all possible interferences in the cross section (S-S, P-P interferences) and in the second case we neglected them, using in our calculations, about 20 S and P resonances. For the evaluation of asymmetry effects (FB, LR and PNC) we realized our own computer codes.

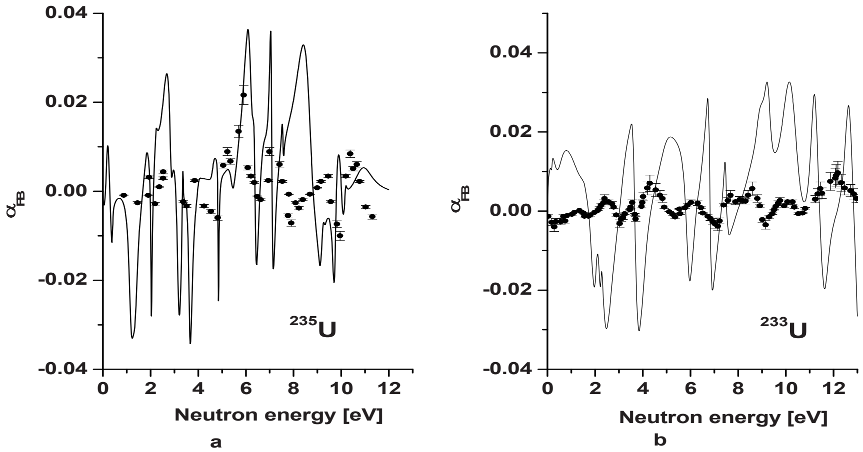

Figure 1. FB effect of fragment emission from neutron fission of a) ^{235}U; b) ^{233}U: – theory; • experiment.

The discovery of PNC effects in the neutron fission on $^{233,235}U$ was unexpected since these nuclei present many S neutron resonances and no P resonances. If new P resonances yield, the presence of many S resonances lead to that the effects will be zero because earlier it was considered that the sign and values of partial widths and phases are random. One way to explain the non zero values of asymmetry effects in fission was given by (Bunakov and Gudkov, 1981), where it was supposed that the sign and values of the phases are not random. In our calculation we used the hypothesis from (Bunakov and Gudkov, 1981), since for the incident neutron energy of few eV the sign and values of the phases are not changing consistently (9). The presence of many resonances gives the large numbers of minima and maxima in the energetic dependences of asymmetry effects (Figures 1-3). If the resonance interferences are neglected in the cross section between S-S and P-P pairs FB and LR effects in some regions reach values higher than 0.5 and PNC effect in the same regions is of order of percents. Earlier such high values were not confirmed experimentally.

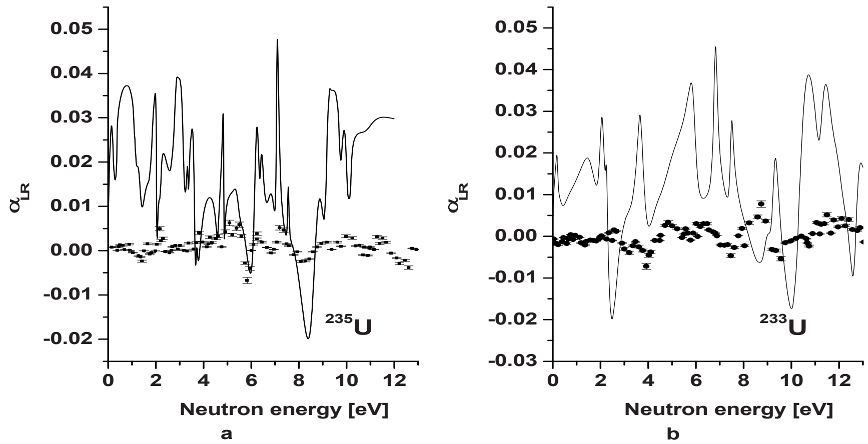

Figure 2. LR effect of fragment emission from neutron fission of a) ^{235}U; b) ^{233}U : – theory; • experiment.

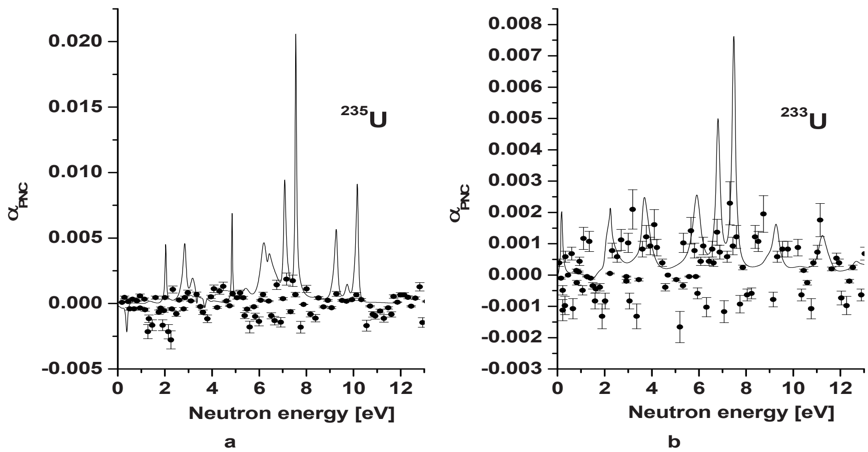

Figure 3. PNC effect of fragment emission from neutron fission of a) ^{235}U; b) ^{233}U : – theory; • experiment.

All the interferences will contribute to the fission cross section which is included in the denominators of asymmetry effects thus "modulating" them. Concerning the present results these mean that the values and the sign of phases are not random in agreement with (Bunakov and Gudkov, 1981), and consequently the number should be reduced to a few P resonances.

The present evaluation of PNC effect is only qualitative for both nuclei and shows the order of magnitude of this effect. This happens because pairs of S-P resonances with the same spin and opposite parities yield and each pair will be characterized by a weak matrix element that could be different from one pair to another. The weak matrix element for $^{233,\,235}$U nuclei is of order of meV as in the paper of (Bunakov and Gudkov, 1981).

4. Conclusions

In this paper by the employed theoretical approach only few P-resonances as contributing to the observed asymmetries were theoretically described. Taking into account the results and considerations done in the present research the experimental data on asymmetry effects in fission of $^{233,\,235}$U should be further analyzed.

Another way is to use a different approach with statistical assumptions managing with a large number of interfering resonances. In the future we'll conduct our studies in this direction in parallel with the need to get new experimental data.

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